THE OPERATIONAL AMPLIFIER

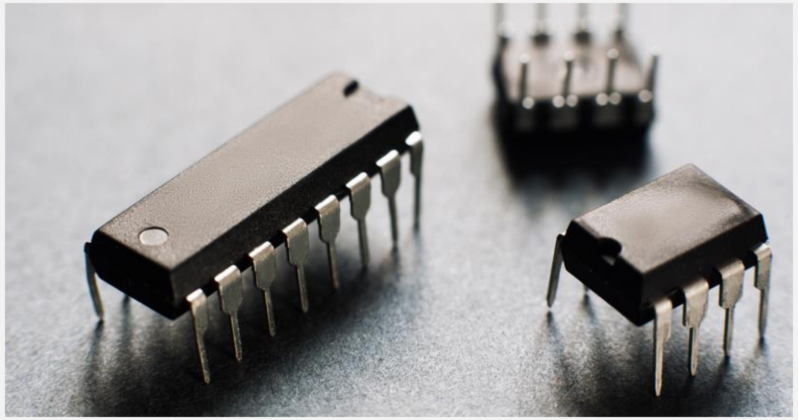
Lecture 8

OVERVIEW

- Introduction to Operational Amplifiers
- Op-Amp Input Modes
- Op-Amp Parameters
- Negative feedback
- Op-Amps with Negative Feedback
- Basic Op-Amp Circuits

THE OPERATIONAL AMPLIFIER

- Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation—thus the term operational. These early devices were constructed with vacuum tubes and worked with high voltages. Today’s op-amps are linear integrated circuits (ICs) that use relatively low DC supply voltages and are reliable and inexpensive.



THE OPERATIONAL AMPLIFIER

- Op-Amp has two input terminals, the inverting (−) input and the noninverting (+) input, and one output terminal.
- Most op-amps operate with two DC supply voltages, one positive and the other negative, although some have a single DC supply.
- Usually, DC voltage terminals are left off the schematic symbol for simplicity but are understood to be there

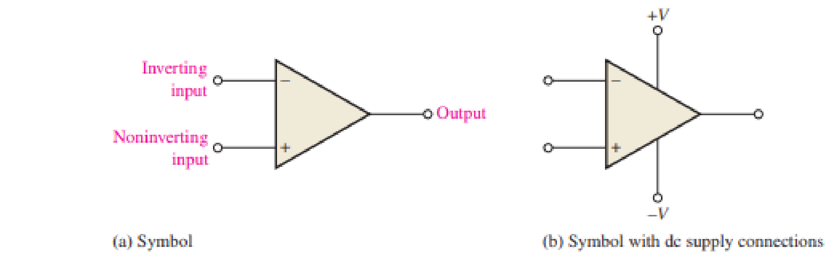


FIGURE 12–1
Op-amp symbols and packages.

THE IDEAL OP-AMP

- The ideal op-amp has infinite voltage gain and infinite bandwidth.
- It has an infinite input impedance (open), so that it does not load the driving source.
- It has zero output impedance.
- The input voltage, V_{in}, appears between the two input terminals
- The output voltage is $A_v V_{in}$

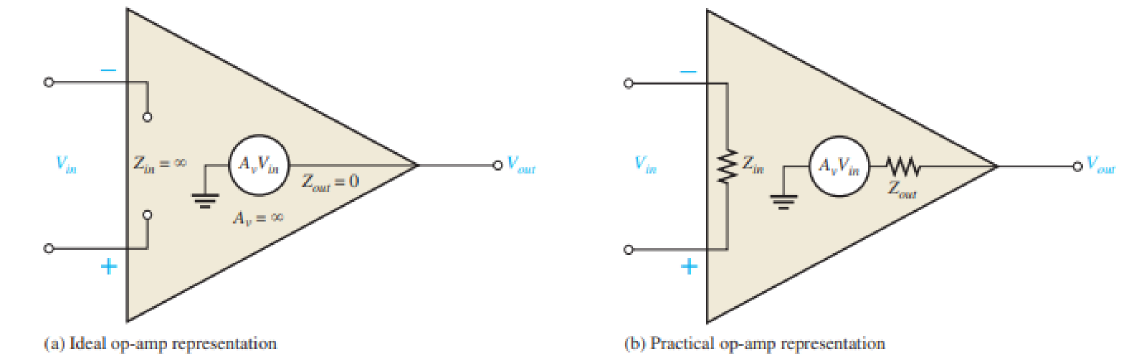


FIGURE 12–2

Basic op-amp representations.

THE PRACTICAL OP-AMP

- Op-amps have both voltage and current limitations.
- Peak-to-peak output voltage is usually limited to slightly less than the two supply voltages.
- Output current is also limited by internal restrictions such as power dissipation and component ratings.

- Practical op-amps have:
  - Very high voltage gain
  - Very high input impedance
  - Very low output impedance

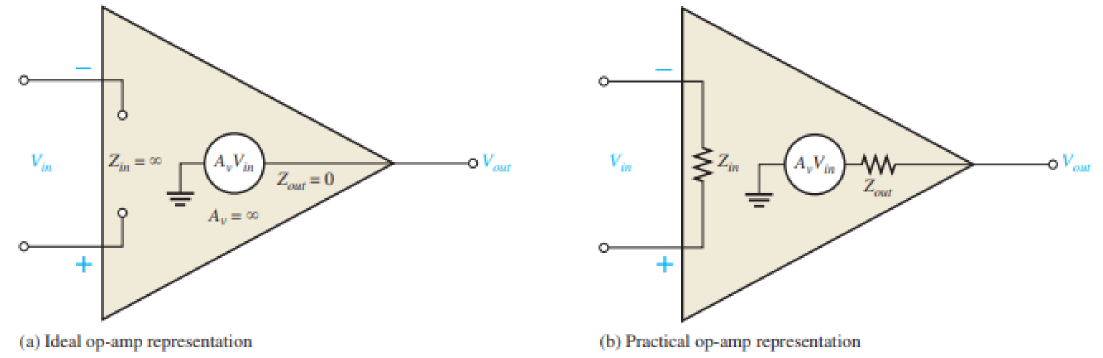


FIGURE 12–2

Basic op-amp representations.

- There is always noise generated within the op-amp.
- Noise is an undesired signal that affects the quality of a desired signal.
- Circuit designers are using smaller voltages that require high accuracy, so low-noise components are in greater demand.

OP-AMP
INTERNAL BLOCK DIAGRAM

- A typical Op-amp is made up of 3 types of amplifier circuits:
  - **A differential amplifier** – provides amplification of the difference voltage between two inputs
  - **A voltage amplifier** – provides additional gain
  - **A push-pull amplifier** – used for output stage, additional voltage amplifier stage.

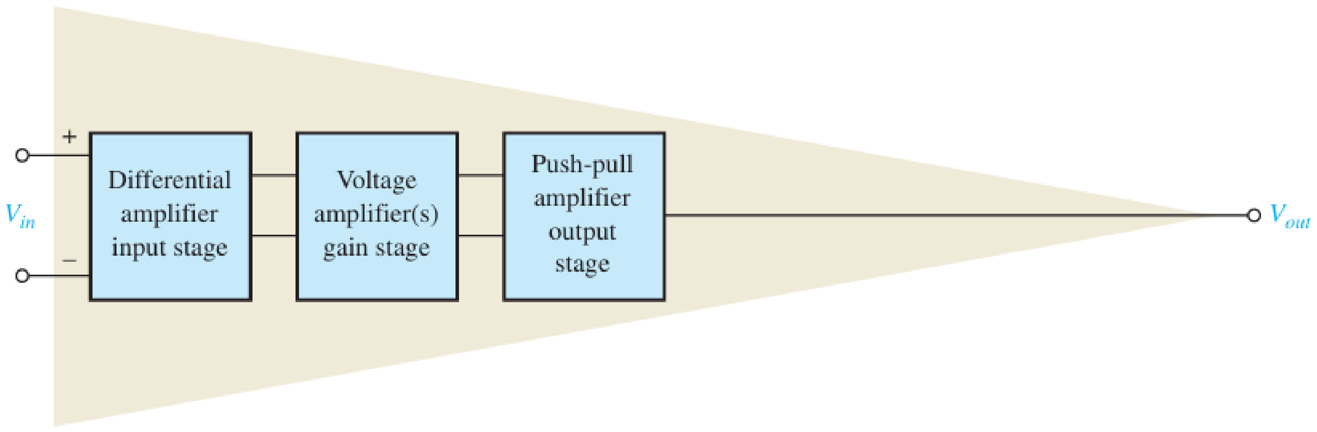


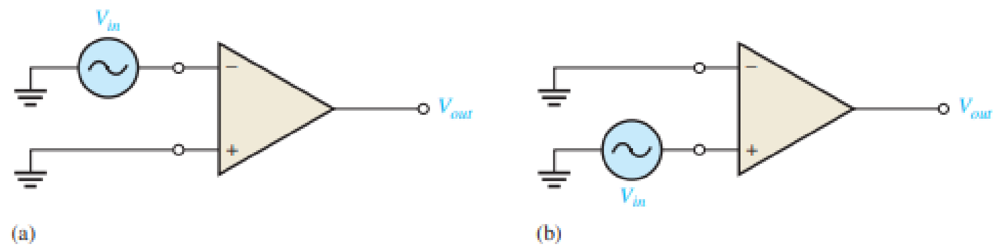
FIGURE 12–3

Basic internal arrangement of an op-amp.

OP-AMP INPUT MODES

- **Differential mode**
  - One signal is applied to an input with the other input grounded:
    - In the case where the signal voltage is applied to the inverting input as in (**a**), an inverted, amplified signal voltage appears at the output.
    - In the case where the signal is applied to the non-inverting input with the inverting input grounded, as in (**b**), a noninverted, amplified signal voltage appears at the the output.

FIGURE 12–4
Single-ended differential mode.

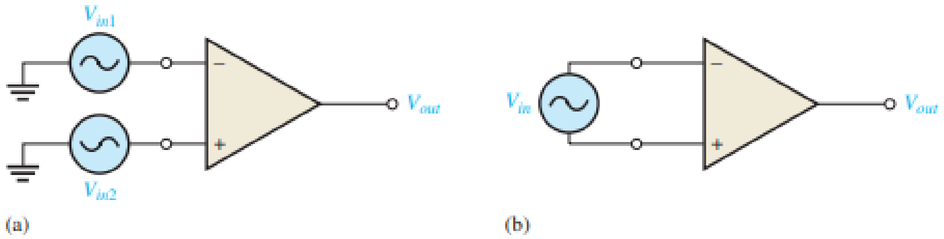


OP-AMP INPUT MODES

- **Differential mode**
  - Two opposite-polarity signals are applied to the inputs:
    - The amplified difference between the two inputs appears on the output. Equivalently, the double-ended differential mode can be represented by a single source connected between the two inputs.

FIGURE 12–5

Double-ended differential mode.

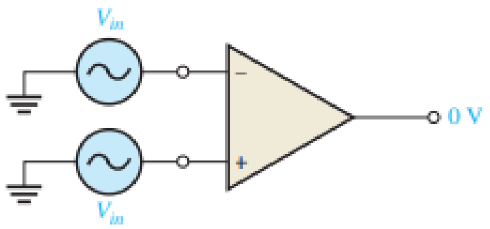


OP-AMP INPUT MODES

- **Common mode**
  - Two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs
  - When equal input signals are applied to both inputs, they tend to cancel, resulting in a zero output voltage. This action is called *common-mode rejection*.
  - **Common-mode rejection:**
    - ✓ Important where an unwanted signal appears commonly on both op-amp inputs.
    - ✓ It means that this unwanted signal will not appear on the output and distort the desired signal.
  - Common-mode signals (noise) generally are the result of the pick-up of radiated energy on the input lines, from adjacent lines, the 60 Hz power line, or other sources

FIGURE 12–6

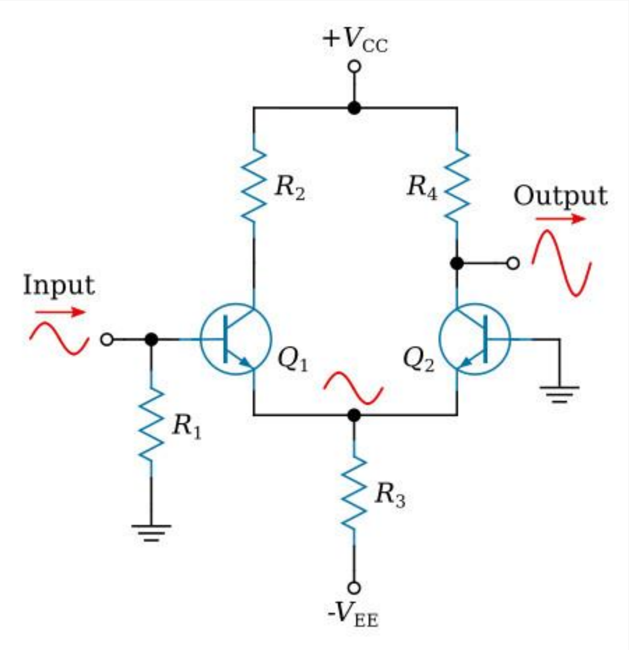
Common-mode operation.



SINGLE-INPUT SINGLE-OUTPUT DIFFERENTIAL AMPLIFIER

- When the input signal developed by R_1 goes positive, the current through Q_1 increases. This increased current causes a positive-going signal at the top of R_3. This signal is felt on the emitter of Q_2. Since the base of Q_2 is grounded, the current through Q_2 decreases with a positive-going signal on the emitter. This decreased current causes less voltage drop across R_4. Therefore, the voltage at the bottom of R_4 increases and a positive-going signal is felt at the output.

- When the input signal developed by R_1 goes negative, the current through Q_1 decreases. This decreased current causes a negative-going signal at the top of R_3. This signal is felt on the emitter of Q_2. When the emitter of Q_2 goes negative, the current through Q_2 increases. This increased current causes more of a voltage drop across R_4. Therefore, the voltage at the bottom of R_4 decreases and a negative- going signal is felt at the output



OP-AMP PARAMETERS

- Common-Mode Rejection Ratio (CMRR)
- Open-Loop Voltage Gain
- Maximum Output Voltage Swing
- Input Offset Voltage
- Input Bias Current
- Input Impedance
- Input Offset Current
- Output Impedance
- Slew Rate
- Noise Specification

OP-AMP PARAMETERS

- **Common-Mode Rejection Ratio (CMRR)**: The measure of an amplifier's ability to reject common-mode signals.
- Ideal op-amp provides a very high gain for differential-mode signals and zero gain for common-mode signals.
- Practical op-amps do exhibit a very small common-mode gain (usually much less than 1), while providing a high open-loop differential voltage gain (usually several thousand).
- The higher the open-loop gain with respect to the common-mode gain, the better the performance of the op-amp in terms of rejection of common-mode signals.
- A good measure of the op-amp's performance in rejecting unwanted common-mode signals is the ratio of the open-loop differential voltage gain, A_{ol}, to the common-mode gain, A_{cm}. This ratio is *the common-mode rejection ratio*, **CMRR**.

$$CMMR = \frac{A_{ol}}{A_{cm}}$$

- The higher the CMRR, the better. A very high value of CMRR means that the open-loop gain, A_{ol}, is high and the common-mode gain, A_{cm}, is low.

OP-AMP PARAMETERS

- **Open-loop voltage gain, A_{ol}**, represents the ratio of output voltage to input voltage when there are no external components. It is set entirely by the internal design.
- A CMRR of 100,000, for example, means that the desired input signal (differential) is amplified 100,000 times more than the unwanted noise (common-mode). If the amplitudes of the differential input signal and the common-mode noise are equal, the desired signal will appear on the output 100,000 times greater in amplitude than the noise.
- **Maximum Output Voltage Swing ($V_{O(p-p)}$)** With no input signal, the output of an op amp is ideally 0 V. This is called the *quiescent output voltage*. When an input signal is applied, the ideal limits of the peak-to-peak output signal are $\pm V_{CC}$. In practice, however, this ideal can be approached but never reached. $V_{O(p-p)}$ varies with the load connected to the op-amp and increases directly with load resistance.
- **Input Offset Voltage** The ideal op-amp produces zero volts out for zero volts in. In a practical op-amp, however, a small DC voltage, $V_{OUT(error)}$, appears at the output when no differential input voltage is applied. The input offset voltage, V_{OS}, is the differential DC voltage required between the inputs to force the output to zero volts. Typical values of input offset voltage are in the range of 2 mV or less.

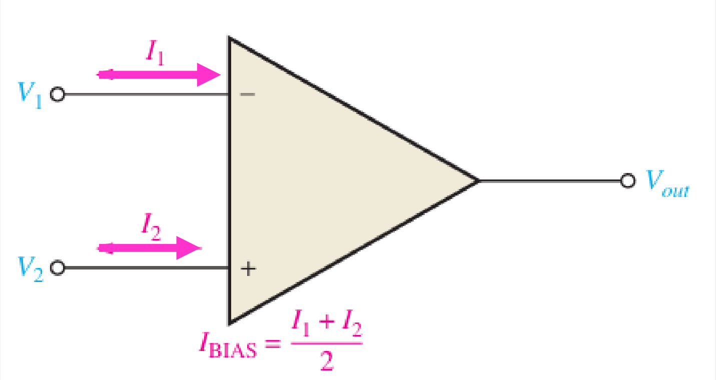
OP-AMP PARAMETERS

- **Input Bias Current** The input bias current is the DC current required by the inputs of the amplifier to properly operate the first stage. By definition, the input bias current is the average of both input currents and is calculated as follows:

$$\boldsymbol{I_{BIAS} = \frac{I_1 + I_2}{2}}$$

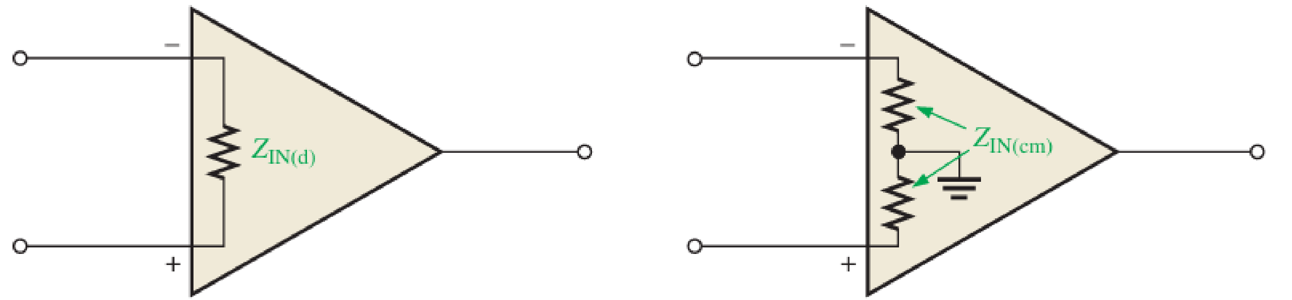
- **Input Offset Current** Ideally, the two input bias currents are equal, and thus their difference is zero. In a practical op-amp, however, the bias currents are not exactly equal. The input offset current, I_{OS}, is the difference of the input bias currents, expressed as an absolute value.

$$I_{OS} = |I_1 - I_2|$$



OP-AMP PARAMETERS

- **Input Impedance** The differential input impedance is the total resistance between the inverting and the noninverting inputs. Differential impedance is measured by determining the change in bias current for a given change in differential input voltage. The common-mode input impedance is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage.

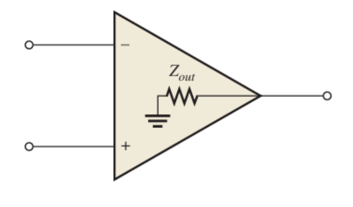


(a) Differential input impedance

(b) Common-mode input impedance

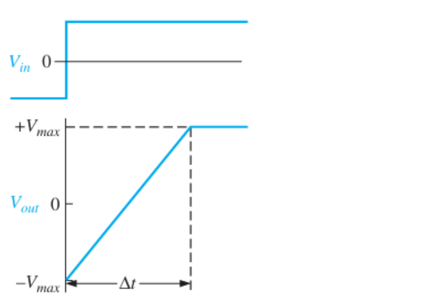
OP-AMP PARAMETERS

- **Output Impedance** the resistance viewed from the output terminal of the op-amp.



- **Slew Rate** The maximum rate of change of the output voltage in response to a step input voltage is the *slew rate* of an op-amp. The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp. The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit:

$$Slew\ rate = \frac{\Delta V_{out}}{\Delta t}$$



(b) Step input voltage and the resulting output voltage

- **Noise Specification** Noise is defined as an unwanted signal that affects the quality of a desired signal. When the op-amp is added to a circuit, additional noise contributions are added from other circuit elements, such as the feedback resistors or any sensors. At low frequencies, noise is inversely proportional to the frequency; Above a critical noise frequency, the noise becomes flat and is spread out equally across the frequency spectrum. For operational amplifiers, noise level is specified relative to the input at a specific frequency above the noise critical frequency.

NEGATIVE FEEDBACK

- **Negative feedback** is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes (or subtracts from) the input signal.
- The inverting input effectively makes the feedback signal 180° out of phase with the input signal.
- Without negative feedback, a small input voltage drives the op-amp to its saturated output states (limits) and it becomes nonlinear.
- Provides a controlled, stable voltage gain, controlled input and output impedance, amplifier bandwidth.

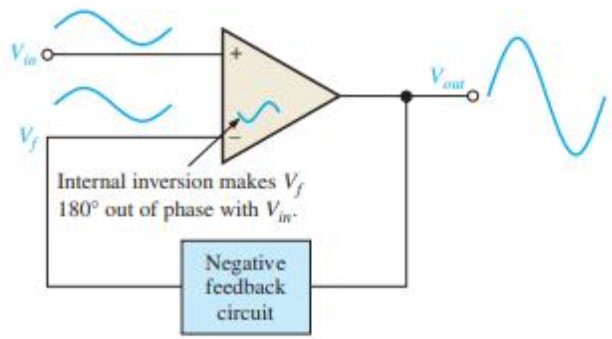


FIGURE 12–14
Illustration of negative feedback.

OP-AMPS WITH NEGATIVE FEEDBACK

An op-amp can be connected using negative feedback to stabilize the gain and increase frequency response. Negative feedback takes a portion of the output and applies it back out of phase with the input, creating an effective reduction in gain. This closed loop gain is usually much less than the open-loop gain and independent of it.

Closed-Loop Voltage Gain, $\boldsymbol{A_{cl}}$ The closed-loop voltage gain is the voltage gain of an op-amp with external feedback. The amplifier configuration consists of the op-amp and an external negative feedback circuit that connects the output to the inverting input. The closed-loop voltage gain is determined by the external component values and can be precisely controlled by them.

Noninverting Amplifier The input signal is applied to the noninverting (+) input. The output is applied back to the inverting input through the feedback circuit (closed loop) formed by the input resistor R_i and the feedback resistor R_f. Resistors R_i and R_f form a voltage-divider circuit, which reduces V_{out} and connects the reduced voltage V_f to the inverting input. The feedback voltage is expressed as

$$V_f = \left(\frac{Ri}{Ri + Rf}\right) V_{out}$$

$$A_{cl(NI)} = \frac{R_i + R_f}{R_i}$$

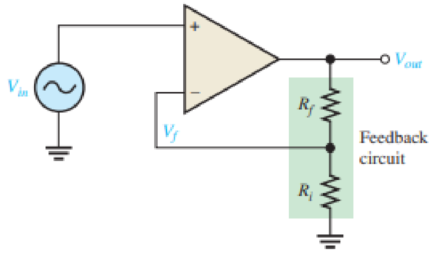


FIGURE 12–16

Noninverting amplifier.

OP-AMPS WITH NEGATIVE FEEDBACK

- **Voltage-Follower** The voltage-follower configuration is a special case of the noninverting amplifier where all of the output voltage is fed back to the inverting (−) input by a straight connection. The straight feedback connection has a voltage gain of 1 (which means there is no gain).
- **Inverting Amplifier** An op-amp connected as an inverting amplifier with a controlled amount of voltage gain. The input signal is applied through a series input resistor R_i to the inverting (−) input. Also, the output is fed back through R_f to the same input. The non-inverting (+) input is grounded. The closed loop gain is independent of the op-amp's internal open-loop gain. Thus, the negative feed back stabilizes the voltage gain.

$$A_{cl(I)} = -\frac{R_f}{R_i}$$

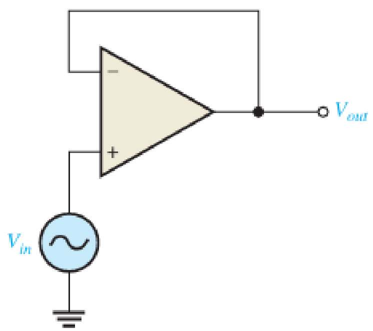


FIGURE 12–19

Op-amp voltage-follower.

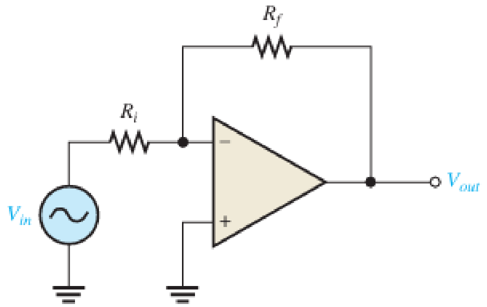


FIGURE 12–20

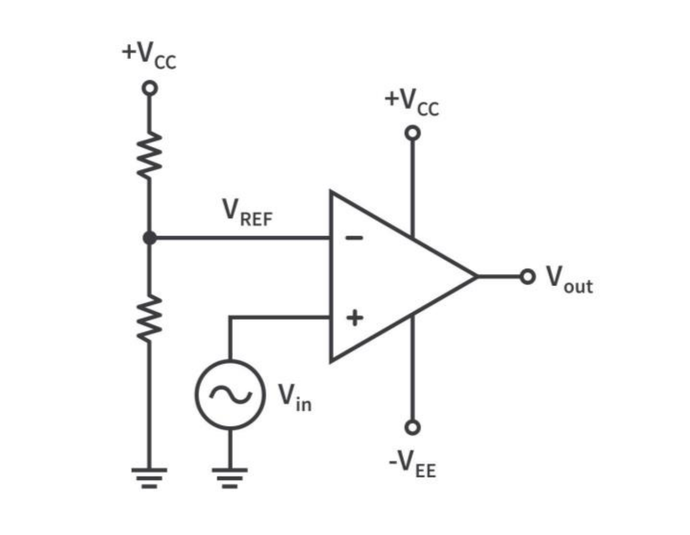
Inverting amplifier.

BASIC OP-AMP CIRCUITS

- Comparators
- Summing Amplifiers
- Integrators and Differentiators

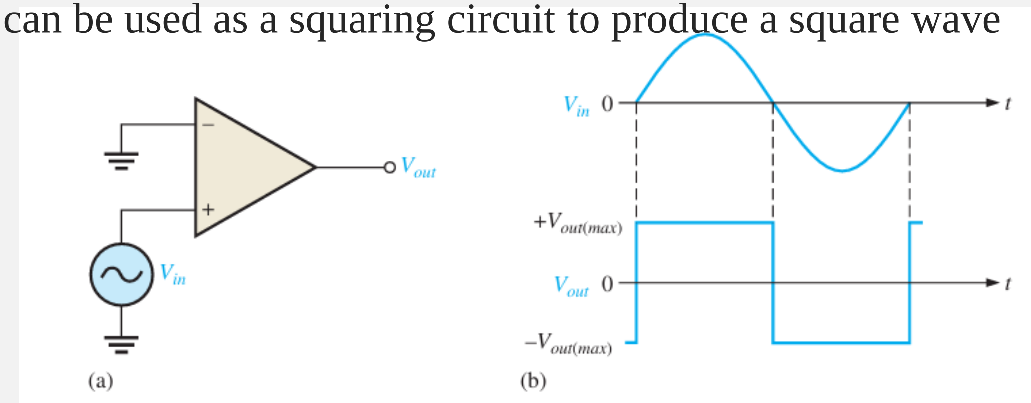
COMPARATORS

- A specialized op-amp circuit that compares two input voltages and produces an output that is always at either one of the two states , indicating the greater or less than relationship between the inputs.
- Provide very fast switching times
- For less critical applications, an op-amp running without negative feedback (open-loop) is often used as a comparator → enables to detect very tiny differences in the inputs as it has very high open-loop gain
- In general, comparators cannot be used as op-amps, but op-amps can be used as comparators in noncritical applications.



COMPARATORS
ZERO-LEVEL DETECTION

- Determine when an input voltage exceeds a certain level.
- As Figure (a) represents, the inverting (−) input is grounded to produce a zero level and that the input signal voltage is applied to the noninverting (+) input.
- Because of the high open-loop voltage gain, a very small difference voltage between the two inputs drives the amplifier into saturation, causing the output voltage to go to its limit.
- Figure (b) shows the result of a sinusoidal input voltage applied to the noninverting input of the zero-level detector.
- When the sine wave is positive, the output is at its maximum positive level.
- When the sine wave crosses 0, the amplifier is driven to its opposite state and the output goes to its maximum negative level.
- As you can see, the zero-level detector can be used as a squaring circuit to produce a square wave from a sine wave.



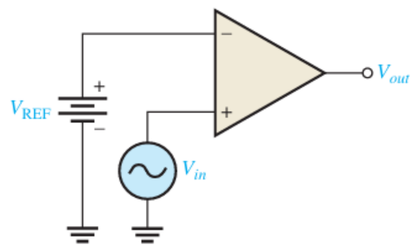
COMPARATORS
NONZERO-LEVEL DETECTION

- Detect positive and negative voltages by connecting a fixed reference voltage source to the inverting (−) input.
- A more practical arrangement is shown in Figure (b) using a voltage divider to set the reference voltage, V_{REF}, as follows:

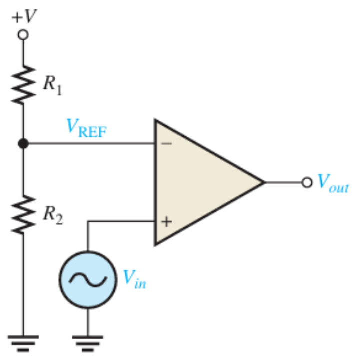
$$V_{REF} = \frac{R_2}{R_1 + R_2}(+V)$$

where +V is the positive op-amp dc supply voltage.

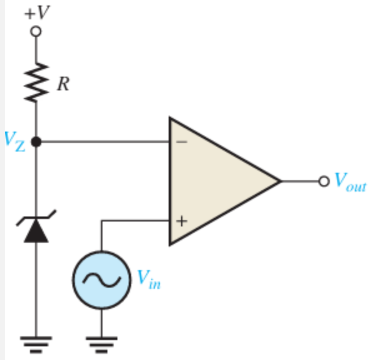
- The circuit in Figure (c) uses a Zener diode to set the reference voltage ($V_{REF} = V_Z$).
- As long as V_{in} is less than V_{REF}, the output remains at the maximum negative level. When the input voltage exceeds the reference voltage, the output goes to its maximum positive voltage, as shown in Figure (d) with a sinusoidal input voltage.



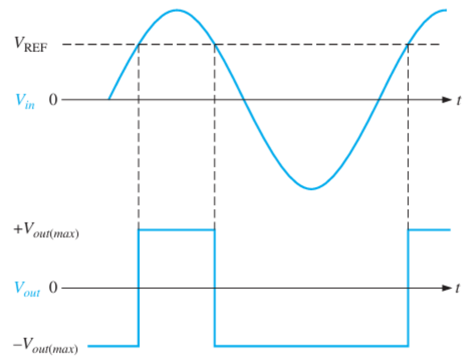
(a) Battery reference



(b) Voltage-divider reference



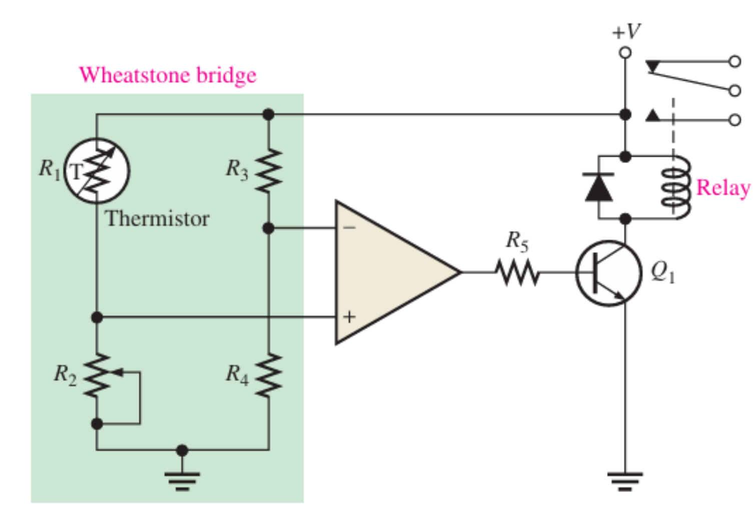
(c) Zener diode sets reference voltage



(d) Waveforms

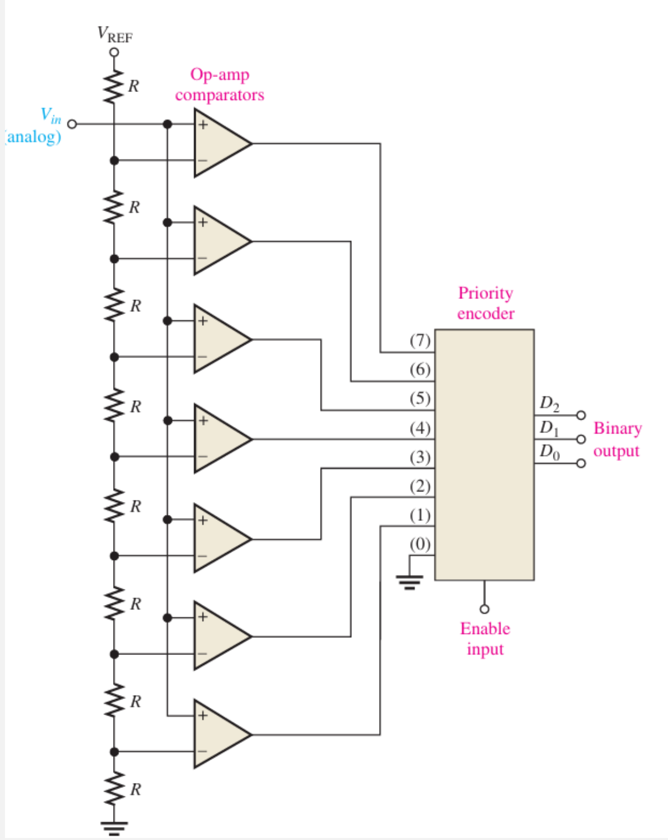
COMPARATOR APPLICATIONS

- Over-Temperature Sensing Circuit
  - A precision over-temperature sensing circuit to determine when the temperature reaches a certain critical value.
  - At normal temperatures (below critical), R_1 is greater than R_2, thus creating an unbalanced condition that drives the op-amp to its low saturated output level and keeps transistor Q_1 off.
  - As the temperature increases, the resistance of the thermistor decreases. When the temperature reaches the critical value, $R_1 = R_2$, and the bridge becomes balanced (since $R_3 = R_4$). At this point the op-amp switches to its high saturated output level, turning Q_1 on. This energizes the relay, which can be used to activate an alarm or initiate an appropriate response to the over-temperature condition.



COMPARATOR APPLICATIONS

- Analog-to-Digital (A/D) Conversion
  - Figure shows an analog-to-digital converter (ADC) that produces three-digit binary numbers on its output, which represent the values of the analog input voltage as it changes.
  - When the input voltage exceeds the reference voltage for a given comparator, a high level is produced on that comparator’s output.
  - The output of each comparator is connected to an input of the *priority encoder*.
  - The *priority encoder* is a digital device that produces a binary number on its output representing the highest value input. The encoder samples its input when a pulse occurs on the enable line (sampling pulse), and a three-digit binary number proportional to the value of the analog input signal appears on the comparators' outputs.



SUMMING AMPLIFIERS (WITH UNITY GAIN)

- A summing amplifier has two or more inputs, and its output voltage is proportional to the negative of the algebraic sum of its input voltages.
- Two voltages, V_{IN1} and V_{IN2}, are applied to the inputs and produce currents I_1 and I_2, as shown.
- Using the concepts of infinite input impedance and virtual ground, it can be determined that the inverting input of the op-amp is approximately $0\ V$ and has no current through it. This means that the total current I_T, which goes through R_f divides into I_1 and I_2 at summing point A.

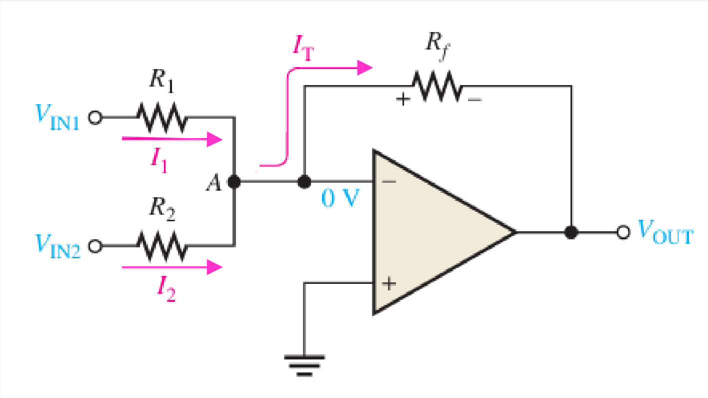
$$I_T = I_1 + I_2$$

- Since $V_{OUT} = -I_T R_f$, the following steps apply:

$$V_{OUT} = -(I_1 + I_2)R_f = -\left(\frac{V_{IN1}}{R_1} + \frac{V_{IN2}}{R_2}\right)R_f$$

- If all three of the resistors are equal ($R_1 = R_2 = R_f = R$), then

$$V_{OUT} = -\left(\frac{V_{IN1}}{R} + \frac{V_{IN2}}{R}\right)R = -(V_{IN1} + V_{IN2})$$



Two-input Summing Amplifier

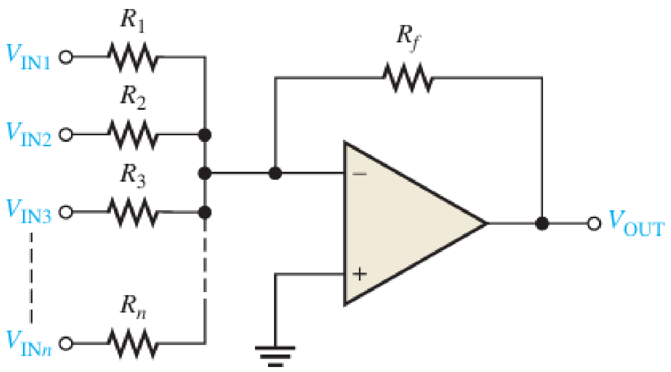
SUMMING AMPLIFIERS (WITH UNITY GAIN)

- A general expression is given below for a unity-gain summing amplifier with n inputs, where all resistors are equal in value.

$$V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3} + \cdots + V_{INn})$$

FIGURE 13–21

Summing amplifier with n inputs.

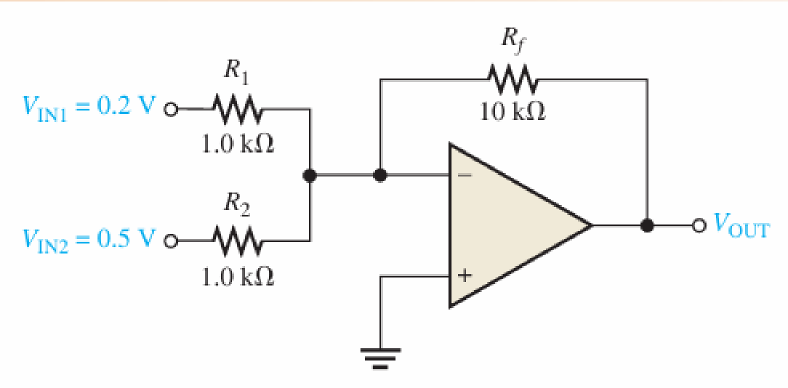


SUMMING AMPLIFIERS (WITH GAIN GREATER THAN UNITY)

- When R_f is larger than the input resistors, the amplifier has a gain of R_f/R, where R is the value of each equal-value input resistor. The general expression for the output is

$$V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2} + \cdots + V_{INn})$$

- The output voltage has the same magnitude as the sum of all the input volt ages multiplied by a constant determined by the ratio $-(R_f/R)$.

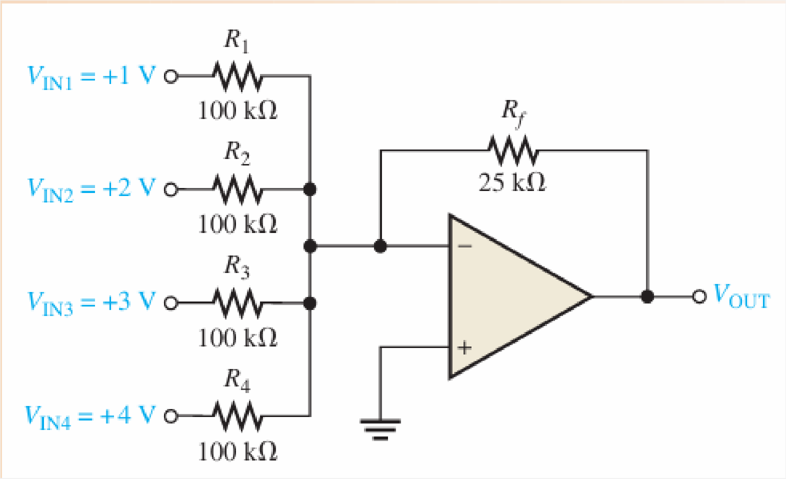


SUMMING AMPLIFIERS
AVERAGING AMPLIFIER

- A summing amplifier can be made to produce the mathematical average of the input voltages. This is done by setting the ratio R_f/R equal to the reciprocal of the number of inputs (n).

$$\frac{R_f}{R} = \frac{1}{n}$$

- The average of several numbers is determined by first adding the numbers and then dividing by the quantity of numbers. A summing amplifier can be designed to do this as illustrated below:

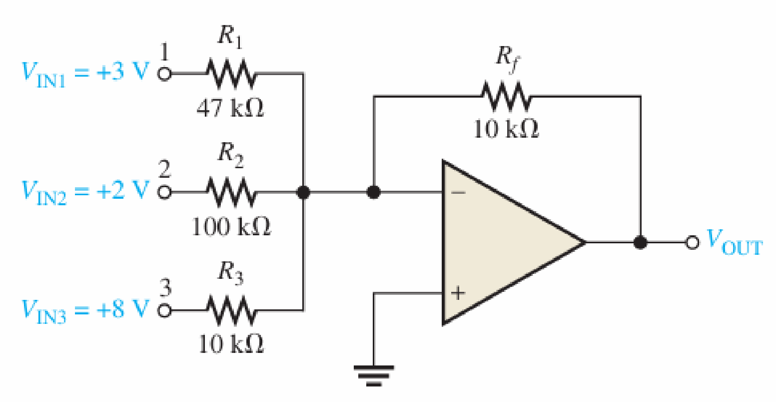


SUMMING AMPLIFIERS
SCALING ADDER

- A different weight can be assigned to each input of a summing amplifier by simply adjusting the values of the input resistors. As you have seen, the output voltage can be expressed as

$$V_{OUT} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \cdots + \frac{R_f}{R_n}V_{INn}\right)$$

- The weight of a particular input is set by the ratio of R_f to the resistance, R_x, for that input ($R_x = R_1, R_2, \ldots R_n$). For example, if an input voltage is to have a weight of 1, then $R_x = R_f$. Or, if a weight of 0.5 is required, $R_x = 2\ R_f$. The smaller the value of input resistance R_x, the greater the weight, and vice versa.

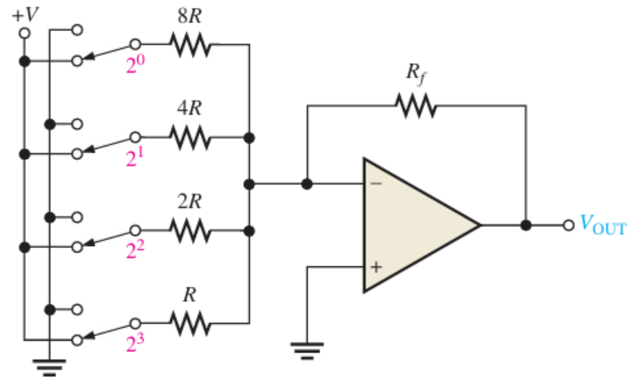


SUMMING AMPLIFIERS
APPLICATION

- **D/A conversion** is an important interface process for converting digital signals to analog (linear) signals. An example is a voice signal that is digitized for storage, processing, or transmission and must be changed back into an approximation of the original audio signal in order to drive a speaker.
- A more common method for D/A conversion is known as the $R/2R$ ladder method. Figure below shows a four-digit digital-to-analog converter (DAC) of this type (called a binary-weighted resistor DAC). The switch symbols represent transistor switches for applying each of the four binary digits to the inputs. The inverting input is at virtual ground, and so the output voltage is proportional to the current through the feedback resistor R_f (sum of input currents). The lowest-value resistor R corresponds to the highest weighted binary input (2^3). All of the other resistors are multiples of R and correspond to the binary weights 2^2, 2^1, and 2^0.

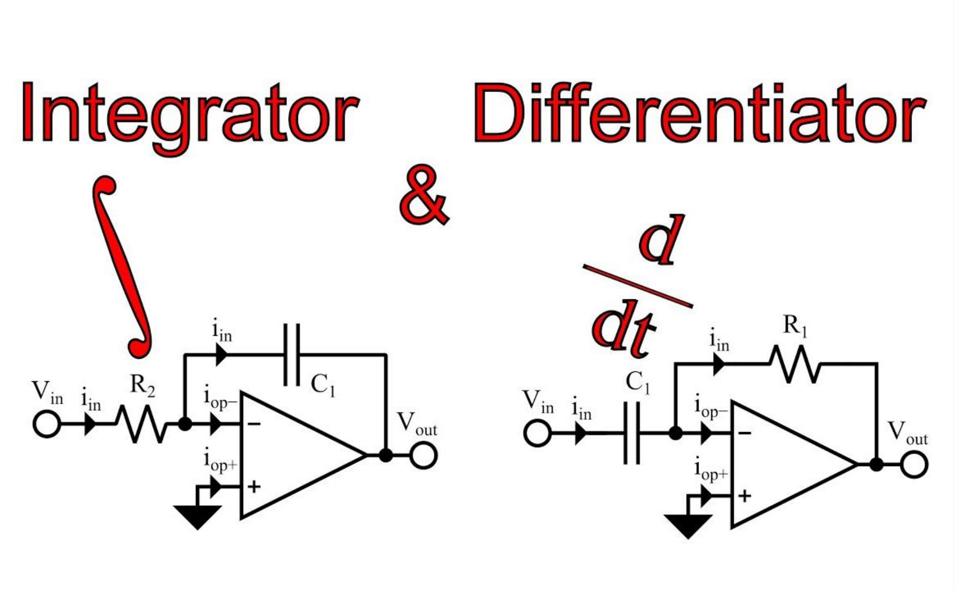
FIGURE 13–26

A scaling adder as a four-digit digital-to-analog converter (DAC).



INTEGRATORS AND DIFFERENTIATORS

- An op-amp **integrator** simulates mathematical integration, which is basically a summing process that determines the total area under the curve of a function.
- An op-amp **differentiator** simulates mathematical differentiation, which is a process of determining the instantaneous rate of change of a function.
- *Practical* **integrators** often have an additional resistor in parallel with the feedback capacitor to prevent saturation.
- *Practical* **differentiators** may include a resistor in series with the comparator to reduce high frequency noise.



THE OP-AMP INTEGRATOR

- The Ideal Integrator
  - The feedback element is a capacitor that forms an RC circuit with the input resistor
  - **How a Capacitor Charges** The charge Q on a capacitor is proportional to the charging current (I_C) and the time (t).

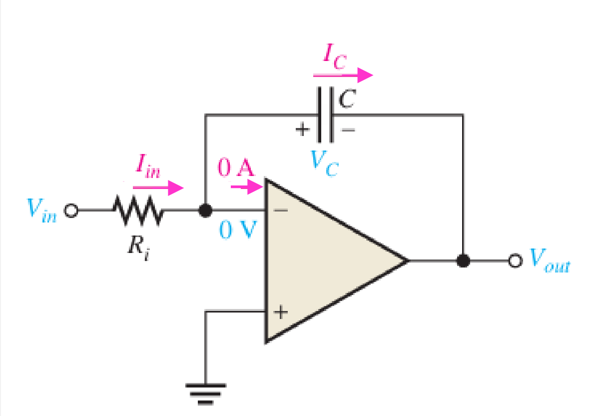
$$Q = I_C t$$

Also, in terms of the voltage, the charge on a capacitor is

$$Q = C\,V_C$$

From these two relationships, the capacitor voltage can be expressed as

$$V_C = \left(\frac{I_C}{C}\right)t$$

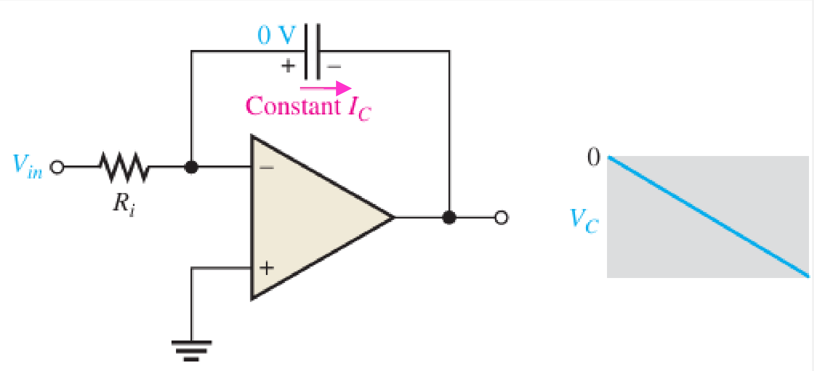


The inverting input of the op-amp is at virtual ground ($0\ V$), so the volt age across R_i equals V_{in}. Therefore, the input current is

$$I_{in} = \frac{V_{in}}{R_i}$$

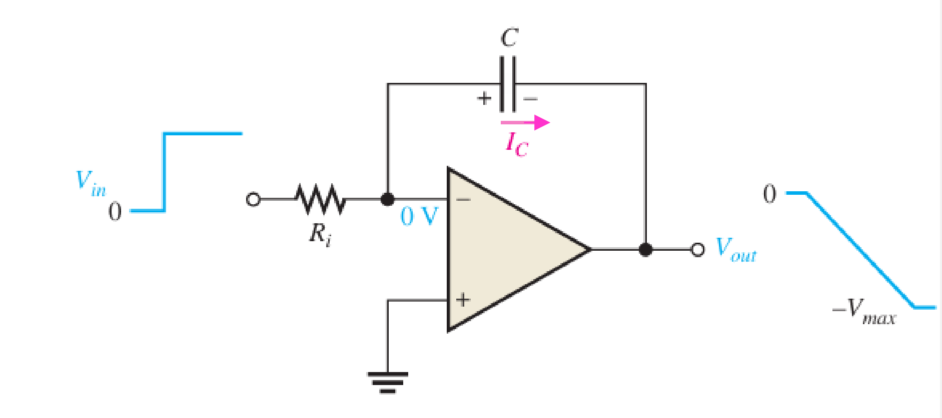
THE OP-AMP INTEGRATOR

- The Ideal Integrator
  - If V_{in} is a constant voltage, then I_{in} is also a constant because the inverting input always remains at $0\ V$, keeping a constant voltage across R_i. Because of the very high input impedance of the op-amp, there is negligible current at the inverting input. This makes all of the input current go through the capacitor, so $I_C = I_{in}$
  - **The Capacitor Voltage.** Since I_{in} is constant, so is I_C. The constant I_C charges the capacitor linearly and produces a linear voltage across C. The positive side of the capacitor is held at $0\ V$ by the virtual ground of the op-amp. The voltage on the negative side of the capacitor, which is the op-amp output voltage, decreases linearly from zero as the capacitor charges. This voltage, V_C, is called a negative ramp and is the consequence of a constant positive input.



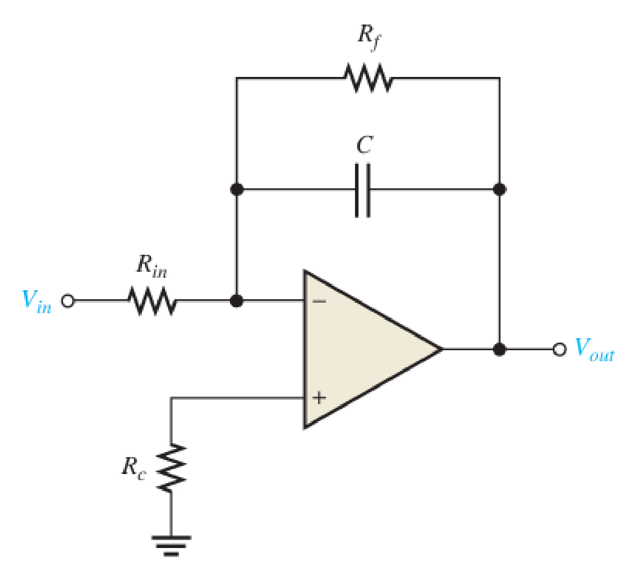
THE OP-AMP INTEGRATOR

- The Ideal Integrator
  - **The Output Voltage.** V_{out} is the same as the voltage on the negative side of the capacitor. When a constant positive input voltage in the form of a step or pulse (a pulse has a constant amplitude when high) is applied, the output ramp decreases negatively until the op-amp saturates at its maximum negative level.



THE OP-AMP INTEGRATOR

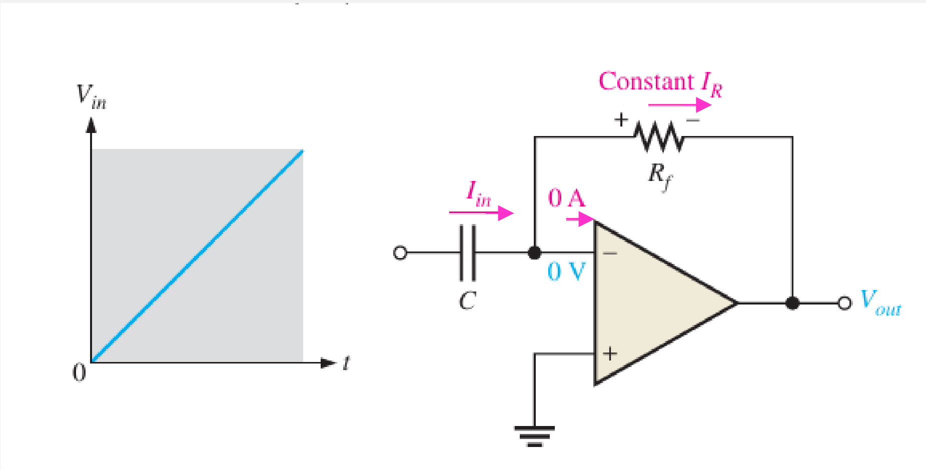
- The Practical Integrator
  - DC error voltage due to offset error will cause the output to produce a ramp that moves toward either positive or negative saturation (depending on the offset), even when no signal is present.
  - Practical integrators must have some means of overcoming the effects of offset and bias current. The simplest solution is to use a resistor in parallel with the capacitor in the feedback path. The feedback resistor, R_f, should be large compared to the input resistor R_{in}, in order to have a negligible effect on the output waveform.
  - A compensating resistor, R_c, may be added to the noninverting input to balance the effects of bias current.



THE OP-AMP DIFFERENTIATOR

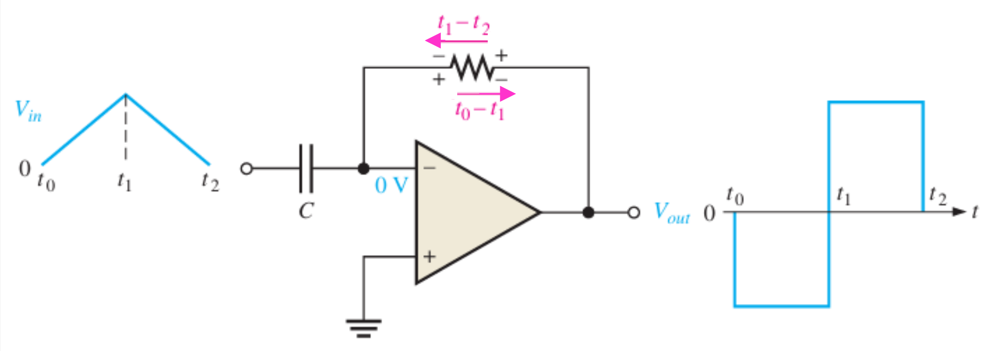
- The Ideal Differentiator
  - Differing from the integrator, the capacitor is now the input element, and the resistor is the feedback element. A differentiator produces an output that is proportional to the rate of change of the input voltage.
  - $I_C = I_{in}$ and the voltage across the capacitor is equal to V_{in} at all times ($V_C = V_{in}$) From the basic formula, the capacitor current is

$$I_C = \left(\frac{V_C}{t}\right)C$$



THE OP-AMP DIFFERENTIATOR

- The Ideal Differentiator
  - Since the current at the inverting input is negligible, $I_R = I_C$. Both currents are constant because the slope of the capacitor voltage (VC/t) is constant. The output voltage is also constant and equal to the voltage across R_f because one side of the feedback resistor is always $0\ V$ (virtual ground).
  - $V_{out} = I_R R_f = I_C R_f$
  - $V_{out} = -\left(\frac{V_C}{t}\right) R_f C$



- The output is negative when the input is a positive-going ramp and positive when the input is a negative-going ramp. During the positive slope of the input, the capacitor is charging from the input source and the constant current through the feedback resistor is in the direction shown. During the negative slope of the input, the current is in the opposite direction because the capacitor is discharging.
- If the slope increases, V_{out} increases. If the slope decreases, V_{out} decreases. The output voltage is proportional to the slope (rate of change) of the input. The constant of proportionality is the time constant, $R_f C$.

THE OP-AMP DIFFERENTIATOR

- The Practical Differentiator
  - As a capacitor has very low impedance at high frequencies, the combination of R_f and C form a very high gain amplifier at high frequencies. This means that a differentiator circuit tends to be noisy because electrical noise mainly consists of high frequencies. The solution to this problem is simply to add a resistor, R_{in}, in series with the capacitor to act as a low-pass filter and reduce the gain at high frequencies. The resistor should be small compared to the feedback resistor in order to have a negligible effect on the desired signal.